

Lenticular galaxies with UV-rings

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By using the public UV imaging data obtained by the GALEX (Galaxy Ultraviolet Explorer) for nearby galaxies, we have compiled a list of lenticular galaxies possessing ultraviolet rings – starforming regions tightly confined to particular radial distances from galactic centers. We have studied large-scale structure of these galaxies in the optical bands by using the data of the SDSS (Sloan Digital Sky Survey): we have decomposed the galactic images into large-scale disks and bulges, have measured the ring optical colours from the residual images after subtracting model disks and bulges, and have compared the sizes of the rings in the optical light and in the UV-band. The probable origin of the outer starforming ring appearances in unbarred galaxies demonstrating otherwise the regular structure and homogeneously old stellar population beyond the rings is discussed.

1 Introduction

According to the Hubble's classification, lenticular galaxies, as an intermediate class between ellipticals and spiral galaxies, possess large-scale stellar disks but lack noticeable starforming sites. This criterium refers to the optical-band images of galaxies. However the recent morphological survey of nearby galaxies in the UV-bands undertaken by the GALEX space telescope [12] has demonstrated that star formation is present in lenticular galaxies more often than it has been thought before, and a typical pattern of the star formation in lenticular galaxies is a large-scale ring.

Large-scale rings in disk galaxies are well-known structures; their classification is established long ago and is related to their origin. Few and Madore [10] analysed a sample consisting of 69 ring galaxies and divided all the rings into two types – ‘O-rings’ and ‘P-rings’. The former class included regular smooth rings with the galactic nuclei in their centers, the latter type had inhomogeneous distributions of surface brightness along the rings and the geometrical centers displaced often with respect to the galactic nuclei. The counts of ‘satellites’ – smaller galaxies around the hosts of the rings – proved that ‘P-rings’ are probably collisional structures formed after the satellite crossing the main galaxy disks. The ‘O-rings’ did not relate necessarily to galaxy interaction; they might be resonance structures. Schwarz [20] considered the response of a large-scale gaseous disk to a bar (non-axisymmetrical distortion of the disk gravitational potential) and found that in course of its dynamical evolution the gas had to accumulate in a ring located at the outer Lindblad resonance of the bar. Evidently, the gas accumulation there could lead to a star formation burst in the ring at this particular radius. Buta and Crocker [5] analysed observational statistics of metric sizes of the rings for a sample of a few hundred galaxies and confirmed that the rings were related to bar resonances. However, several unbarred galaxies are also known that have regular starforming rings; every such case requires individual analysis after which a conclusion follows usually that the galaxy has experienced a minor merger having produced this ring [23].

After the results of the nearby galaxy survey in the UV-bands by the GALEX have become available, the researchers have reported outer UV-rings in several regular lenticular galaxies lacking star formation signatures in the optical bands. The UV-rings have been noted in IC 4200 [21], NGC 2962 [18], ESO 381-47 [7], NGC 4262 [4], and in NGC 404 [26]; they may have either collisional or resonance origin, with various probability degree in every particular case. We think that the very rise of a starforming ring in a lenticular galaxy otherwise lacking significant gas supply or young stars may be related to its transformation from a spiral galaxy. Here we present the first sample of regular lenticular galaxies with the UV-rings which can be used for a statistical analysis, and discuss possible origin of these rings in minor mergers. To exclude evidently resonance-triggered rings which do not need galaxy interaction for their formation, we take only unbarred galaxies.

2 The sample

Firstly, we have looked at the UV-images of the nearby galaxies included into the Atlas by Gil de Paz et al. [12] and have identified the galaxies with the ring morphology in the UV-bands. Only the galaxies observed also by the SDSS are included into our sample because we want to have a possibility to compare the UV and optical morphologies of our targets. Secondly, we have used the list of ringed galaxies compiled by Kostyuk [15] by inspecting the Palomar Atlas images, such that these galaxies have outer rings in the optical blue band. For the unbarred S0-galaxies from

Table 1: Global parameters of the galaxies under consideration

Galaxy	Type NED ¹	V_r (km/s) NED	D(Mpc), ² NED	R_{25} , '' RC3 ³	m_B RC3	M_B LED4 ⁴	$u - r$ NED	HI? NED	Environment NED
IC 522	S0	5079	71	30	13.97	-20.8	2.75	–	single+satellite
MCG 11-22-15	–	8064	114	24 ⁴	15.6 ⁴	-19.9	–	–	a group member
NGC 252	(R)SA0 ⁺ (r)	4938	71	45	13.35	-21.3	0.97 ⁶	+	a group center
NGC 446	(R)SAB0 ⁰	5446	76.5	61	13.35	-21.0	–	+	in a pair
NGC 809	(R)S0 ⁺ :	5367	74	44	14.66 ⁵	-19.9	2.69	–	single+3 sat
NGC 934	SAB0 [–]	6353	88	40	14.04	-20.7	2.69	–	a group member
NGC 4344	SB0:	1142	14.5	50	13.34	-18.2	2.02	+	a Virgo member
NGC 4513	(R)SA0 ⁰	2304	34	43	14.01	-19.0	2.61	+	in a wide pair
NGC 6028	(R)SA0 ⁺ :	4475	62.5	40	14.35	-20.0	2.76	+	a group center
NGC 6340	SA0/a(s)	1198	20	97	11.87	-20.0	2.78	+	a group center
NGC 6534	S?	8332	117.5	25	15.40	-20.1	–	–	isolated
NGC 7808	(R')SA0 ⁰ :	8787	122	38	13.48	-21.3	2.59	–	in a pair+5 sat
UGC 4599	(R)SA0 ⁰	2072	26	60	13.6	-17.5	2.45	+	a group center
UGC 5936	(R)SA0 ⁺ :	7230	99	39	14.21	-21.0	2.66	–	in a triplet

¹NASA/IPAC Extragalactic Database

²distance from the NED, with respect to the Local Group

³Third Reference Catalogue of Bright Galaxies [28]

⁴Lyon-Meudon Extragalactic Database

⁵the blue magnitude b_j , from the APM [16]

⁶it is a colour $B - V$ instead of $u - r$ which is absent in the NED

the Kostyuk's list we have retrieved the GALEX images by exploring facilities of the NED links and have found several UV-bright outer rings among these galaxies too.

For all S0-galaxies found to possess UV-rings we have retrieved g ($\lambda 4686 \text{ \AA}$) and r ($\lambda 6165 \text{ \AA}$) digital images from the public data archives of the SDSS, DR7 [1] and DR8 [2], to search for the rings in the optical bands and to compare the properties of the 'optical' rings with those in the UV.

The final sample includes 14 S0-galaxies; their global properties taken from the extragalactic databases are listed in the Table 1.

3 Surface photometry in the optical bands

Our processing with the optical images included:

- constructing $g - r$ colour maps for the initial (full) galaxy images;
- decomposing every galaxy into a large-scale Sersic bulge and exponential disk(s) in g -band and in r -band independently;
- deriving residual images by subtracting the obtained model images bulge+disk(s) from the initial (full) galaxy images;
- constructing $g - r$ colour maps for the residual images.

All the calculations besides the decomposition have been made with the software by V. Vlasyuk [27]; the photometric calibration information has been taken from the SDSS WEB-site. The decompositions, and also the colour profiles for the residual images, were made with the software GIDRA [19]. To fit the initial (full) images of the galaxies, we applied a model consisting of two exponential disks with different scalelengths and of a Sersic bulge. With such models, all the galaxies except NGC 4344 were modelled quite finely. To describe the surface brightness profiles of NGC 4344, only two exponential segments are enough; taking into account also the inner structure of the galaxy, we conclude that probably NGC 4344 has no bulge at all. The results of the decompositions in the g - and r -bands for all galaxies of the sample which are characterized by the central brightnesses and Sersic-law scalelengths are presented in the Table 2.

Table 2: Photometric parameters of the galaxy decompositions

Galaxy	Band	Outer disk		Inner disk		Bulge		
		$r_0, ''$	$\mu_0, \text{mag/arcsec}^2$	$r_0, ''$	$\mu_0, \text{mag/arcsec}^2$	$r_0, ''$	$\mu_0, \text{mag/arcsec}^2$	n
IC 522	r	27.8	23.4	5.9	19.3	2.37	12.7	1.0
IC 522	g	22.3	23.6	5.8	20.1	2.26	13.5	1.0
MCG 11-22-15	r	10.7	26	5.2	23.2	1.51	15.5	1.9
MCG 11-22-15	g	11.0	25.5	4.9	24.3	1.54	16.4	1.9
NGC 252	r	73	24.5	14.9	20.5	3.73	17.4	1.5
NGC 252	g	58	24.7	12.1	21.2	4.13	18.9	1.6
NGC 446	r	23.9	24.9	11.5	22.7	3.32	14.5	1.8
NGC 446	g	23.3	25.4	12.1	23.3	2.9	15.5	1.8
NGC 809	r	18.0	23.8	10.2	19.5	1.4	17.2	1.2
NGC 809	g	20.3	23.1	10.3	20.5	2.33	15.8	1.4
NGC 934	r	35	23.0	7.3	20.7	2.24	15.3	2.1
NGC 934	g	42.6	24.3	7.0	21.4	2.01	16.6	1.8
NGC 4344	r	47.1	22.9	10.3	19.8	–	–	–
NGC 4344	g	62.5	24.4	10.7	20.2	–	–	–
NGC 4513	r	79.3	23.7	8.9	21.3	1.97	15.8	1.5
NGC 4513	g	63	24	10.1	22.3	2.15	16.5	1.6
NGC 6028	r	25	21.8	10.0	19.5	1.77	14.3	2.2
NGC 6028	g	25	22.4	12.4	21.8	1.66	15.1	2.2
NGC 6340	r	50.4	22.2	20.3	20.0	5.17	15.1	1.9
NGC 6340	g	73.3	22.9	22.1	20.8	5.23	15.3	2.0
NGC 6534	r	15.7	21.3	7.6	20.2	1.95	17.2	1.8
NGC 6534	g	14.2	22.9	6.9	20.7	2.31	18.2	1.8
NGC 7808	r	46	24.3	7.6	20.2	2.66	16.2	1.7
NGC 7808	g	63	24.9	8.6	21.3	2.93	17.3	1.7
UGC 4599	r	56.4	23.8	5.5	19.9	2.24	16.5	2.1
UGC 4599	g	50.1	24.3	5.1	20.3	1.59	17.2	2.1
UGC 5936	r	21.4	24	7.7	21.9	1.82	16.1	1.5
UGC 5936	g	23.4	24.8	7.3	22.6	1.82	16.9	1.5

4 The results: ring parameters

The general conclusions which we can made from our calculations are the following:

- if to exclude NGC 809 and MCG 11-22-15 which have red rings, the rings of all other galaxies look rather blue in the visible light;
- the radii of the rings, their location in the galaxies are the same in the UV rays and in the optical bands.

The main parameters of the rings estimated by using the residual images in the optical bands are given in the Table 3. The colours of the rings are measured at the middle radii of the rings; only for UGC 5936 and MCG 11-22-15 we give also the colours at the inner and outer edges of the rings because they differ substantially from the colours at the middle radii: in the middle, the rings in these two galaxies are very blue, and they become redder close to the edges. Let us to discuss the results for the individual galaxies.

IC 522. The galaxy is decomposed into two disks and a Sersic bulge with the exponential brightness profile. After subtracting this model from the galaxy images, we see one more centrally concentrated component in the residuals; due to its red, round appearance, this component may be a small de Vaucouleurs' bulge inside the more extended pseudobulge. The ring looks asymmetric both in the UV and in the optical bands. The galaxy can be treated as practically isolated: according to the NED, it has only one faint satellite.

MCG 11-22-15. The decomposition of the optical images has enlightened the presence of the regular ring and a minibar in the center. The galaxy resembles UGC 5936 by its residual structure; the only difference is the more narrow optical ring extension in the north-western segment of the residual images. We cannot estimate if the UV-ring has a similar squeeze because the spatial resolution of the GALEX images is insufficient. Also we would

Table 3: The characteristics of the rings in the UV and in the optical bands

Galaxy	Optical radii (arcsec)	UV-radii (arcsec)	$g-r$
IC 522	11-24	13-26	0.56
MCG 11-22-15	10-22	14-21	0.90(middle) 1.00(edges)
NGC 252	21-30	22-34	0.30
NGC 446	25-42	25-42	0.84
NGC 809	16-34	7-32	1.15
NGC 934	about 57-80	50-88	0.37
NGC 4344	3-12	2.2-11.5	0.35
NGC 4513	about 60-80	69-83	0.70
NGC 6028	23-40	19-39	0.60
NGC 6340	47-64;25-35;4-20	up to 66	0.69; 0.41; 0.46
NGC 6534	10-21	11-22	0.30
NGC 7808	18-34	23-36	0.65
UGC 4599	39-60	41-58	0.40
UGC 5936	14-38	18-33	0.64(middle) 0.83(edges)

note the rather red optical colour of the ring in this galaxy.

NGC 252. The outstanding peculiarity of the ring in this galaxy is that it is obviously inclined to the main symmetry plane of the galaxy. In the central part of the residual images a spiral pattern is seen that is an argument in favour of the circumnuclear disk presence. The colour residual map demonstrates a very blue $g - r$ of the ring.

NGC 446. The ring is among the reddest ones with its optical colour of $g - r = 0.84$. The galaxy is rich with diffuse matter that is seen both in the optical and UV images. Also the residual images reveal some structure in the center of the galaxy which may be identified as a circumnuclear disk with a spiral pattern.

NGC 809. The residual images of this galaxy contain a lot of interesting details. Besides the very red, probably dust-rich ring, we must note the central minibar with weakly developed spiral arms. The UV- and optical rings demonstrate comparable brightness contrasts.

NGC 934. While the UV-ring of the galaxy is bright, though slightly asymmetric, the optical ring is less impressive and can hardly be distinguished against the noise background of the residual images. Instead, a bright circumnuclear disk is seen both in the UV and in the optical light. The galaxy is a member of a rather rich group.

NGC 4344. As the surface brightness profile of this galaxy implies, NGC 4344 lacks a bulge that is quite unusual for a lenticular galaxy. The ring is strongly inhomogeneous, with bright star forming knots visible both in the UV and in the optical bands. The residual images look asymmetric, with the south-eastern part more rich in matter than the north-western one. The galaxy belongs to the Virgo cluster.

NGC 4513. The outer ring of this galaxy resembles that of NGC 934: it is bright in the UV and faint in the optical bands. The residual $g - r$ colour map reveals another blue ring in the inner part of the galaxy – it cannot be distinguished at the GALEX maps because it is deeply embedded into the UV-bright circumnuclear disk.

NGC 6028. The ring of this galaxy demonstrates a tail-like extension at the south-eastern edge. By the decomposition we have put into evidence a presence of a nuclear minibar. After considering the colour map of the residual image we have concluded that the object seen to the south from the galactic nucleus is probably a foreground star.

NGC 6340. The galaxy is already studied well [22, 6]. The result of our analysis is that it possesses at least three asymmetric rings which are brighter in the optical bands than in the UV. The galaxy locates at the center of a rather rich group.

NGC 6534. The galaxy has two rings. In the optical light the outer ring is blue, it is also seen in the UV; the inner ring is rather red and embedded into the bulge area. The UV-analog of the inner ring cannot be distinguished because of the lower spatial resolution of the GALEX data. Probably, the two rings are inclined to the symmetry

plane of the galaxy under different angles.

NGC 7808. By considering the residual maps of this galaxy, we have discovered a nuclear minibar and another extended structure co-axial with the bar – perhaps, a circumnuclear stellar disk. The ring which is also seen at the residual colour map looks asymmetric and rather faint both in the UV and in the optical light. The galaxy belongs to a small group consisting of only two large galaxies surrounded by small satellites.

UGC 4599. The rings of this galaxy, the inner one being similar to that of NGC 4513 – clearly visible in the optical colour map and looking only a part of the bright circumnuclear disk in the UV, – are rather irregular and consist of several separate arcs. After subtracting the model of ‘a Sersic bulge plus two exponential disks’ from the initial galaxy images in the g and r bands, we have found a small ($2''$), red, round structure in the residual maps in the very center of the galaxy.

UGC 5936. The galaxy has a very regular ring, one of the most impressive in our sample. It resembles somewhat the ring in NGC 809. The residual maps reveal a presence of the nuclear minibar. The star-like object in the south-eastern part of the ring does not belong to the galaxy with a high probability.

5 Discussion: the scenaria of ring formation and evolution

The galaxies of our sample are of S0-type, so first of all, they all possess large-scale stellar disks and Sersic bulges, with a power parameter $n \approx 2$ (see the Table 2, the last right column) that is typical for early-type disk galaxies [13]. And secondly, they almost all have in general rather old stellar populations – because the integrated colour of $u - r$ is larger than 2.22 in all galaxies except NGC 4344 (see the Table 1), and this criterium, according to Strateva et al. [24], attributes them to the ‘red sequence’. The first property enables us to separate our galaxies with the outer starforming rings from the Hoag object which has a de Vaucouleurs’ spheroid – probably an elliptical galaxy in the center of its ring. We would like to stress this difference because some authors – Wakamatsu [29] studying NGC 6028 and Finkelman and Brosch [9] studying UGC 4599 – called them ‘Hoag-like galaxies’; we think that it was wrong.

The galaxies of our sample are homogeneously distributed over all types of environment: they can belong to the field or to groups, among them there are two quite isolated objects and one Virgo member. The half of the sample have been reported to possess neutral hydrogen (see the Table 1); this fraction is in agreement with the known frequency of detecting lenticulars in the 21 cm line [8]. However, the more attentive look at the Table 1 reveals that the galaxies detected in the HI line inhabit the part of the sample nearest to us, so the visible absence of gas in the other half of the sample may be a selection effect.

Our sample includes only unbarred galaxies (see the morphological types in the Table 1; among all, only NGC 4344 is classified by NED as a SB0, but our visual inspection of the SDSS images of this galaxy reveals no bars). It means that we have tried to exclude resonance mechanisms of ring formation in the galaxies under consideration. Some nuclear bars found by us in the sample galaxies during this works are not able to affect the large-scale structure of the galaxies sufficiently to form outer rings, as we argued earlier [14]. We conclude that the most probable mechanism to form the outer starforming rings in the S0 galaxies of the sample is galaxy interaction in its various forms. In the galaxies NGC 7808, NGC 6340, NGC 6028, UGC 4599, IC 522 we observe perhaps the destruction of a satellite by tidal forces from the large host galaxy [11]. This conclusion is implied by the inhomogeneous brightness distributions along the rings in these galaxies and their appearances as tightly wound spirals. The ring formation in NGC 809, NGC 934, NGC 4344, NGC 4513, UGC 5936, MCG 11-22-15, NGC 6534, and NGC 446 was probably the result of a vertical satellite impact onto the central part of the galaxies – they are the Carthwell-like cases. The ring symmetry degree gives evidence for almost central impact in NGC 809, NGC 934, NGC 4513, UGC 5936, and NGC 446 and slightly offset one in NGC 4344 and MCG 11-22-15. Such collisions provoke ringlike density waves in the galactic disks which are described by Athanassoula & Bosma [3] and simulated in particular by Mapelli et al. [17]. The star formation in the ringlike density waves was inevitable if a sufficient amount of gas was present in a disk before the impact.

Some comments about particular galaxies.

NGC 934 and NGC 4513 have the rings which are much brighter in the UV than in the optical bands. We can treat these rings as close relatives of the Type I XUV-disks in spiral galaxies [12]; perhaps it is the earliest stage of the impact-produced rings.

The ring in NGC 4344 is very knotty; it may be classified as the ring of RE-type according to Athanassoula & Bosma [3] criteria. The reason for such fragmentation may be the absence of stabilizing effect from a central mass concentration – we have already noted that the galaxy lacks bulge.

As for the cases of NGC 4513 and UGC 4599, where there are two starforming rings seen in the optical bands but only one seen in the UV, we would involve effects of secular evolution to explain such structures. We would

like to note that the extended UV-disks in the centers of galaxies where in the optical band we see only narrow starforming rings represent a rather frequent phenomenon.

Perhaps, secular evolution is also responsible for the blue ‘middle circle’ seen against the reddish broad rings in UGC 5936 and MCG 11-22-15.

And finally, the inclined ring in NGC 252, with its inhomogeneous and asymmetric optical appearance, must be the result of accreting a satellite from the inclined orbit [3].

6 Conclusions

By using the public data of the GALEX imaging survey of nearby galaxies, we have compiled a list and have fulfilled surface photometry of 14 lenticular galaxies with the UV rings (or, in other words, with the outer starforming rings). The optical colour profiles and the mean colours are calculated for the rings by using the residual images after subtracting the large-scale photometric models constructed from the SDSS g - and r -images.

We have discussed the possible ways to form the outer rings possessing the morphological and photometric properties similar to those found by us in the sample galaxies. Dynamical simulations presented in the literature show a good agreement with our data if the concept of impact or tidal nature of the rings is accepted.

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Appendix

The colour $g - r$ maps of the residual images of the sample galaxies after subtracting the model ‘bulge+disks’ images from the original SDSS images:

1st row – IC 522, MCG 11-22-15, NGC 252;

2nd row – NGC 446, NGC 809, NGC 934;

3rd row – NGC 4344, NGC 4513, NGC 6028;

4th row – NGC 6340, NGC 6534, NGC 7808;

5th row – UGC 4599, UGC 5936.

